hep-ph/0606129
hep-ph/0607090
hep-ph/0611111

# A new model of Higgs bosons

Ryuichiro Kitano (SLAC)

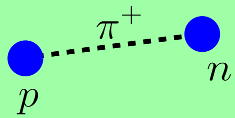
February 15, 2007, Seminar@Fermilab

# Contents

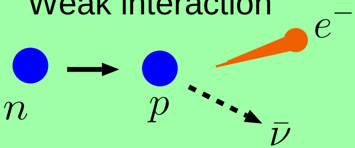
Introduction

## Standard Model

### Strong interaction




### Weak interaction




### Electromagnetism


SU(3)xSU(2)xU(1) gauge theory

$g \qquad W^a \qquad B$

gauge fieds

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \qquad d_R$$

$$l = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix} \qquad e_R$$

matter fieds

$$H = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$$

Higgs fieds

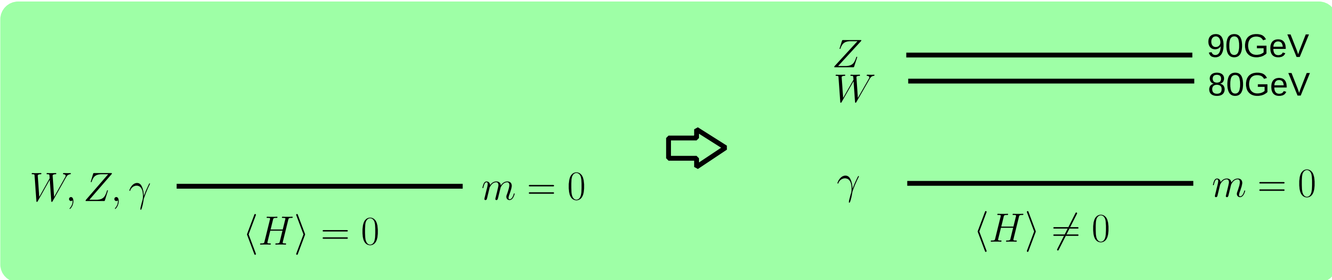
Incredibly beautiful description of particle physics

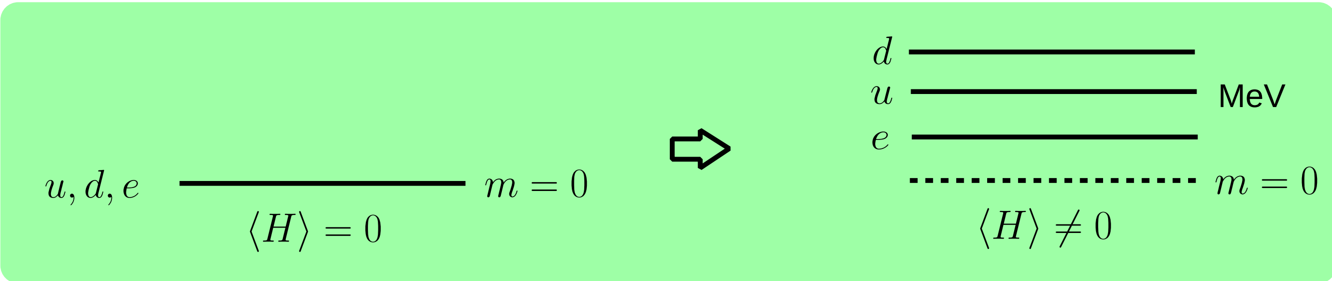
Higgs boson is the key of the success of this model

## Higgs boson

SU(2)xU(1) --> U(1)     $\langle H \rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$ ← vacuum expectation value

⇨ This gives masses for gauge bosons and fermions



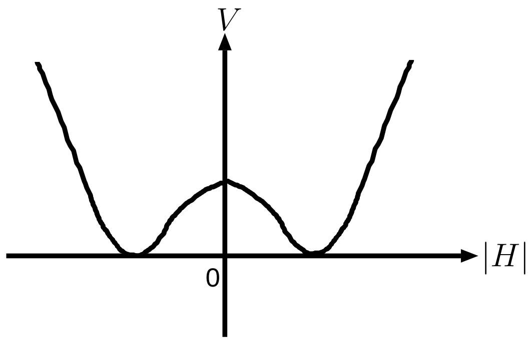

Our world becomes asymmetric while keeping theory beautiful

What's the mechanism for symmetry breaking?

In the Standard Model, it is simply assumed that...

$$V(H) = -m_H^2|H|^2 + \lambda|H|^4$$

such that $\langle H \rangle \neq 0$ minimizes the potential




And.. $m_H^2 \sim O((100\ \mathrm{GeV})^2)$ to reproduce correct size of $G_F$

What determines the scale of symmetry breaking???

Why $m_H^2 \ll M_{\mathrm{Pl}}^2$ ???

What kind of underlying physics made this potential???

O(100-1000GeV) is exactly the energy scale which will be explored at LHC.

→ Serious consideration of this question is necessary before LHC.

We should know what we are looking for.

Supersymmetry

A popular scenario for physics beyond the Standard Model.

Boson $\longleftrightarrow$ Fermion

This symmetry explains why $m_H^2 \ll M_{\rm Pl}^2 \sim (10^{18}\ {\rm GeV})^2$

Fermion masses are stable under quantum corrections --> Boson masses are also stable.

There are many other success of this hypothesis:

1. This theory provides a candidate for dark matter of the universe.

$\Omega_{\rm DM} \sim 0.2$ <-- There is no candidte to explain this in the Standard Model.

but there are new neutral particles:

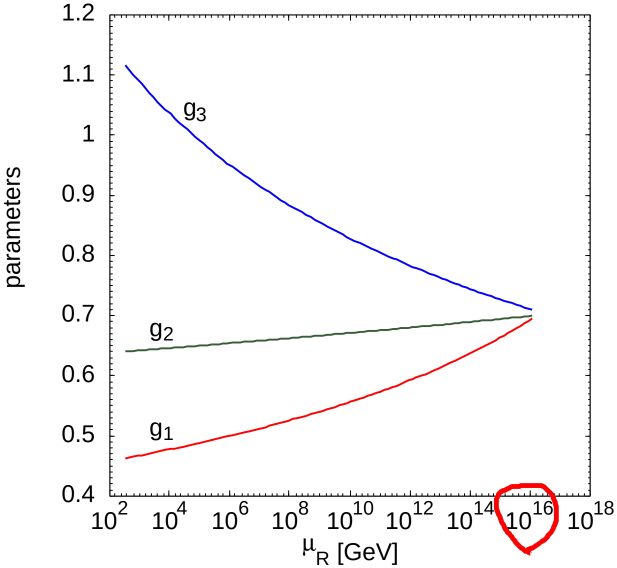
$\tilde{B}^0, \tilde{W}^0, \tilde{h}^0$ : neutralinos

$\tilde{\psi}_{3/2}$ : gravitino

2. Gauge coupling unification

$\Rightarrow$ Grand Unification!!!

# Grand Unification




This is strongly indicating that SU(3)xSU(2)xU(1) is unified into a single interaction at very high energy such as SU(5).

Very non-trivially, all the fermions fit into SU(5) representations.

$q, u, e \longrightarrow$ 10

$l, d \longrightarrow$ 5*

Wow. This is great.

Of course, our world is not that symmetric.

We do not see SU(5) or supersymmetry...

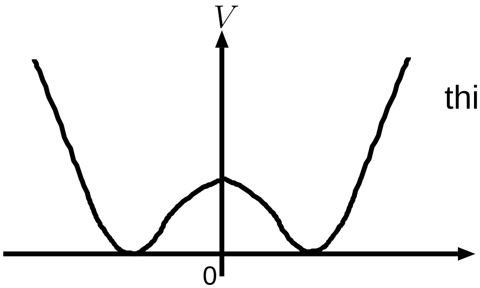
--> We can repeat the same trick of the Higgs field H.

1. SU(5) breaking "Higgs" field $\langle \Sigma \rangle = \begin{pmatrix} 2v & & & & \\ & 2v & & & \\ & & 2v & & \\ & & & -3v & \\ & & & & -3v \end{pmatrix}$

2. Supersymmetry breaking "Higgs" field $\langle F_S \rangle \neq 0$

such that boson and fermion masses split.

Probably there are

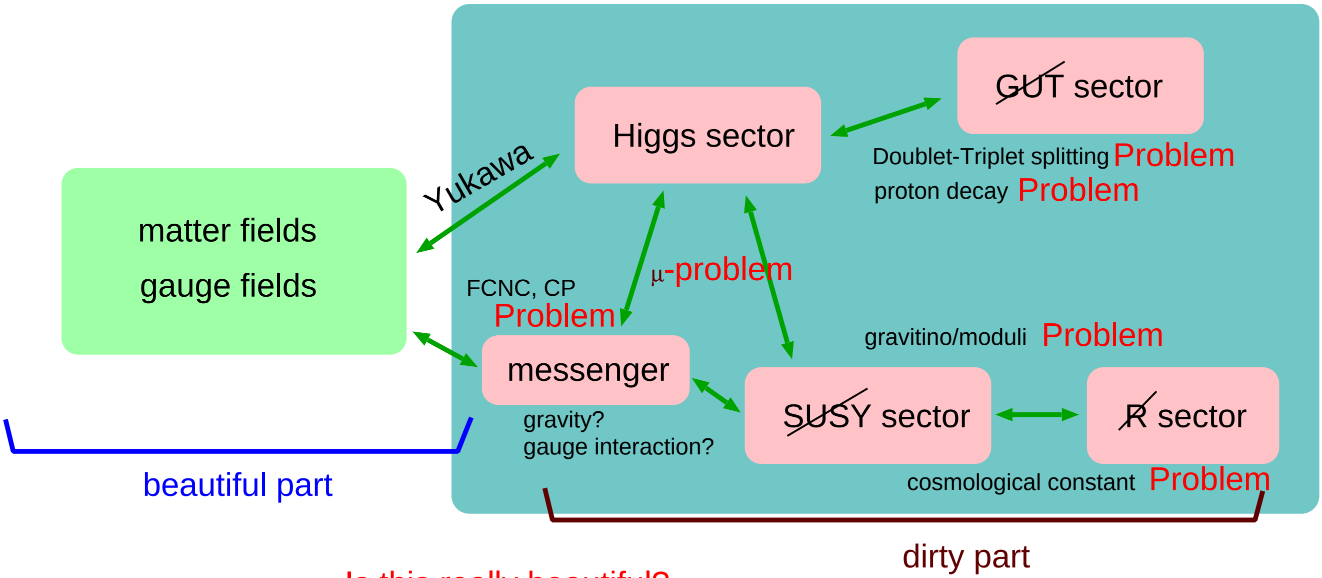



this type of potential for those fields.

Sounds good.

Yes, It sounds like a great framework but actual picture isn't so nice.

The new "Higgs" sector needs to be strange/unnatural.




Is this really beautiful?

What we did is just introducing unknown symmetry breaking sectors
and hide problems there!

We need special interconnection among these sectors!!

A new idea is necessary for a realistic scenario with supersymmety and unification!

Real time model building....

Let's experience the difficulties..

SUSY breaking sector

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

$$W = m^2 S \qquad \left(F_S = m^2 = \sqrt{3} m_{3/2} M_{\rm Pl}\right)$$

Most of the effective theory of SUSY breaking models are of this type.

(O'Raifeartaigh, ISS, IYIT, ...)

Good. Very simple.

Real time model building....

Let's experience the difficulties..

Gravity mediation $m_{3/2} \sim 100\ \mathrm{GeV}$ FCNC/CP

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} \boxed{+\Phi_i^\dagger \Phi_i + \frac{(S^\dagger S)(\Phi_i^\dagger \Phi_j)}{M_{\mathrm{Pl}}^2}} \boxed{+\frac{S^\dagger H \bar{H}}{M_{\mathrm{Pl}}} + h.c.}$$

$$W = m^2 S \qquad \left(F_S = m^2 = \sqrt{3} m_{3/2} M_{\mathrm{Pl}}\right)$$

$\mu \sim m_{3/2} \sim 100\ \mathrm{GeV}$

$$f = \frac{1}{g^2}\left(1 + \boxed{\frac{S}{M_{\mathrm{Pl}}}}\right) \qquad m_{1/2} = \frac{F_S}{M_{\mathrm{Pl}}} \sim m_{3/2} \sim 100\ \mathrm{GeV}$$

moduli/gravitino problem

$S \rightarrow \psi_{3/2}\psi_{3/2} \rightarrow \mathrm{LSPs}$ $\Rightarrow$ gravitino/LSPs overproduction

**Real time model building....**

Let's experience the difficulties..

**Gauge mediation** $m_{3/2} \ll 100\ \mathrm{GeV}$ FCNC/CP

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} \boxed{+\Phi_i^\dagger \Phi_i + \frac{(S^\dagger S)(\Phi_i^\dagger \Phi_j)}{M_{\rm Pl}^2}} \boxed{+\frac{S^\dagger H \bar{H}}{M_{\rm Pl}} + h.c.}$$

$$W = m^2 S \qquad \left(F_S = m^2 = \sqrt{3} m_{3/2} M_{\rm Pl}\right)$$

$$\mu \sim m_{3/2} \ll 100\ \mathrm{GeV}$$

$$f = \frac{1}{g^2} \boxed{+\frac{1}{8\pi^2} \log S} \qquad m_{1/2} = \frac{g^2}{(4\pi)^2}\frac{F_S}{S}$$

We need $\langle S \rangle \neq 0$ . How???

moduli/gravitino problem

$$\cancel{S \to \psi_{3/2}\psi_{3/2} \to \mathrm{LSPs}} \implies$$ ~~gravitino/LSPs overproduction~~

This decay mode becomes subdominant.

It seems that gravity and gauge mediation scenarios are complimentary

Real time model building....

My solution Sweet spot Supersymmetry

Gravity/Gauge mediation $m_{3/2} \sim 1\ \mathrm{GeV}$ FCNC/CP

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} \quad \boxed{+\Phi_i^\dagger \Phi_i + \frac{(S^\dagger S)(\Phi_i^\dagger \Phi_j)}{M_{\mathrm{Pl}}^2}} \quad \boxed{+\frac{S^\dagger H \bar{H}}{\Lambda} + h.c.}$$

$$W = m^2 S \qquad \left(F_S = m^2 = \sqrt{3} m_{3/2} M_{\mathrm{Pl}}\right)$$

$$\mu \sim m_{3/2} \left(\frac{M_{\mathrm{Pl}}}{\Lambda}\right) \sim 100\ \mathrm{GeV}$$

$$\boxed{\mathrm{for} \quad \Lambda \sim 10^{16}\ \mathrm{GeV}}$$

$$f = \frac{1}{g^2} \boxed{+\frac{1}{8\pi^2} \log S}$$

$$m_{1/2} = \frac{g^2}{(4\pi)^2} \frac{F_S}{S}$$

moduli/gravitino problem

$m_{1/2} \sim 100\ \mathrm{GeV}$

by $\langle S \rangle \sim \dfrac{\Lambda^2}{M_{\mathrm{Pl}}}$

$$\boxed{\mathrm{for} \quad \Lambda \sim 10^{16}\ \mathrm{GeV}}$$

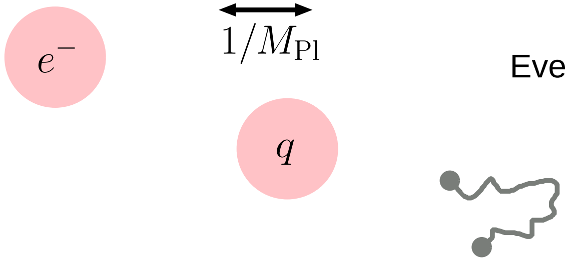
$$\boxed{\Lambda \sim 10^{16}\ \mathrm{GeV}} \Rightarrow$$ Gravitino dark matter!!!

No FCNC/CP, mu or gravitino problems.

Solutions to the mu-problem indicates that SUSY breaking sector and Higgs sector are directly coupled at the GUT scale.

## An idea

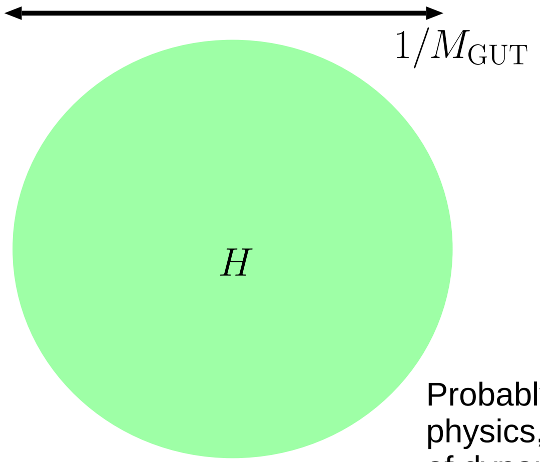
We think something like this happens at the Planck scale




Every particle stops being elementary.

Vibration of strings?

And the idea is....



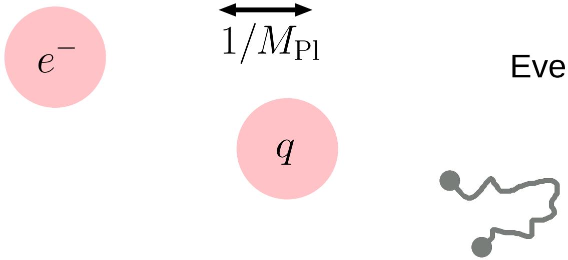

Higgs is by some reason
a bit bigger

Higgs stops being elementary
at the GUT scale.

Probably this is a part of gravity
physics, but I can model this part
of dynamics by the field theory because
gravity is still weak at the GUT scale.

An idea

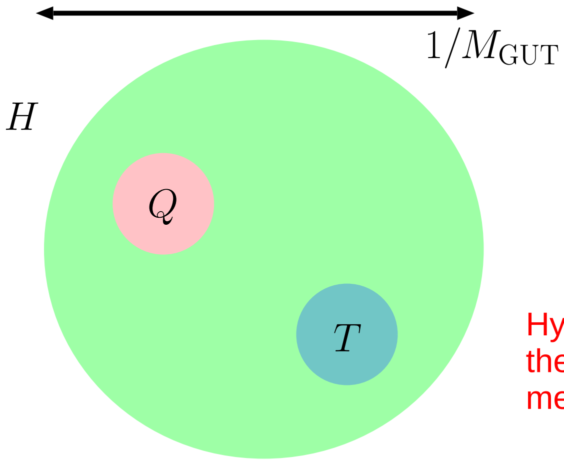
We think something like this happens at the Planck scale




Every particle stops being elementary.

Vibration of strings?

And the idea is....

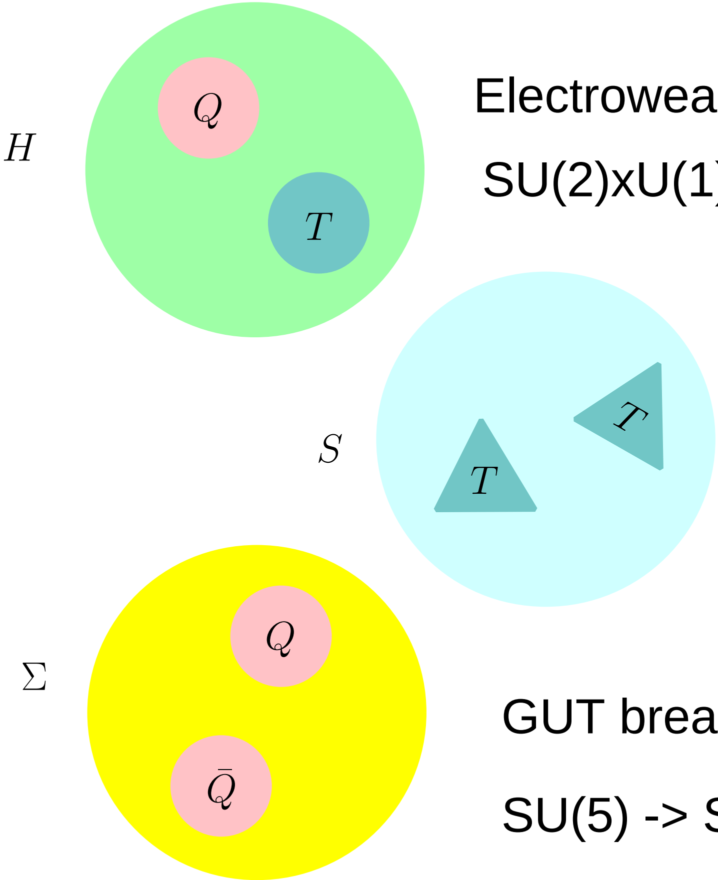



Higgs is by some reason
a bit bigger

Hypothesis:
the Higgs field is a composite
meson made of two "quarks."

This hypothesis greatly simplifies the "Higgs" sectors.

## Unification of all the symmetry breaking sectors into a single dynamics!!




Electroweak symmetry breaking!

SU(2)xU(1) -> U(1)

Supersymmetry breaking!!

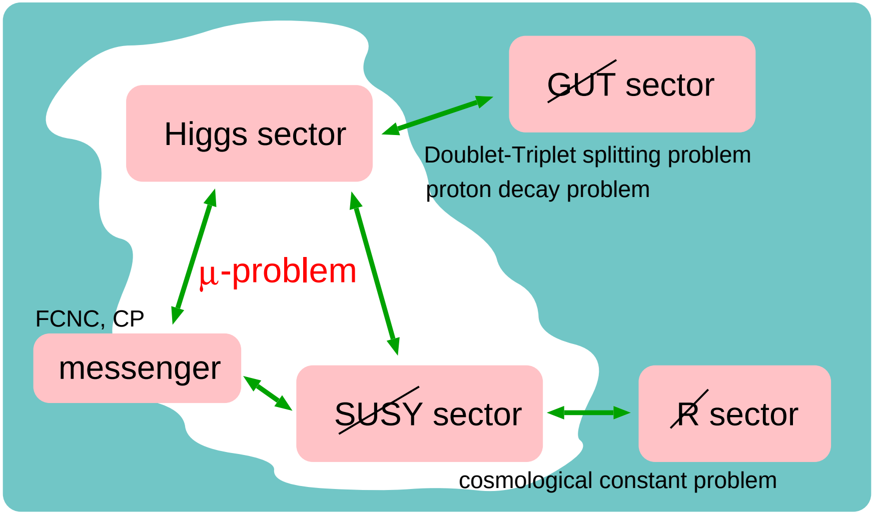
GUT breaking!

SU(5) -> SU(3)xSU(2)xU(1)

μ-problem

The special coupling between the Higgs and SUSY breaking sectors.

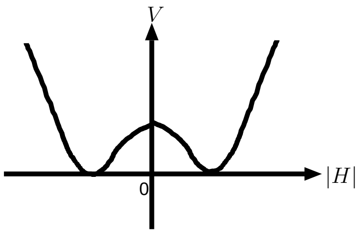
Let's clean up the dirty sector by step by step.




Higgs potential:

$$V = \mu^2|H|^2 \qquad -m_H^2|H|^2 \qquad +\frac{g^2}{8}|H|^4$$

Supersymmetric term SUSY breaking term




We need

$$\mu^2 \sim m_H^2 \sim M_W^2 ???$$

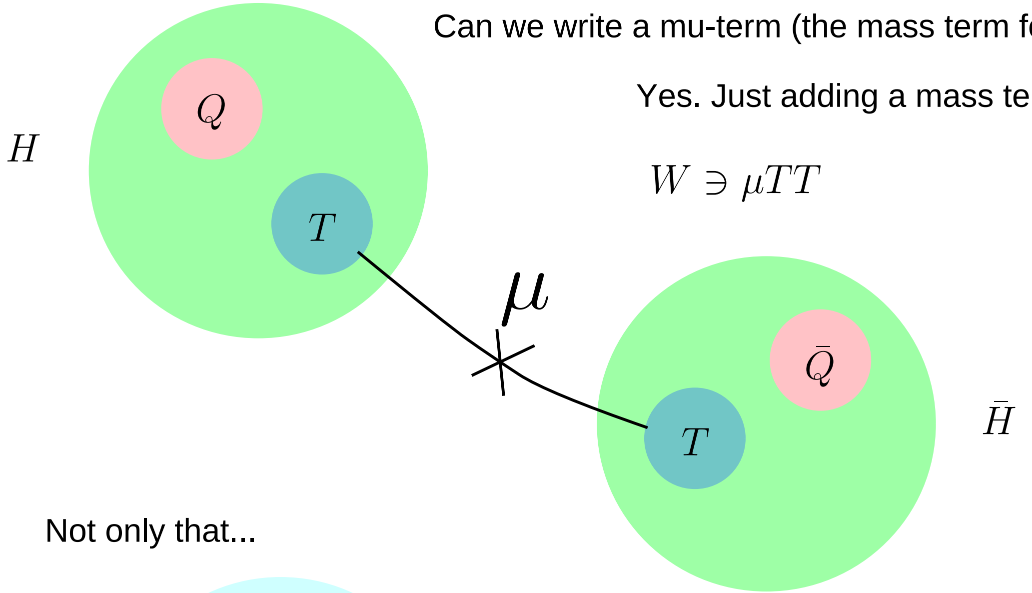
Why?

## μ-driven SUSY breaking

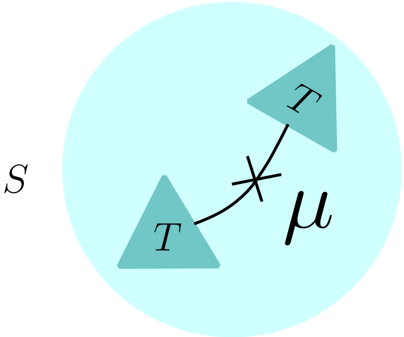
Can we write a mu-term (the mass term for the Higgs boson)?

Yes. Just adding a mass term for T.

$$W \ni \mu TT$$




Not only that...



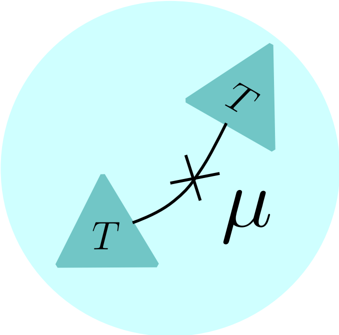

[Intriligator,Seiberg,Shih '06]

Fermion pair condensation!! Dynamical SUSY breaking!!!

$$\rightarrow \quad F_S = \langle TT \rangle / \Lambda = \mu\Lambda$$

## μ-driven SUSY breaking

$S$




$$W \ni \mu T T$$

$$\downarrow$$

$$W \ni \mu \Lambda S$$

$$K \ni \frac{S^\dagger H \bar{H}}{\Lambda} + h.c.$$

$$\left( S \sim \frac{(TT)}{\Lambda} \right)$$

μ-term!!

$$\boxed{F_S = \mu \Lambda}$$

$$\boxed{m_H^2 \ ?}$$

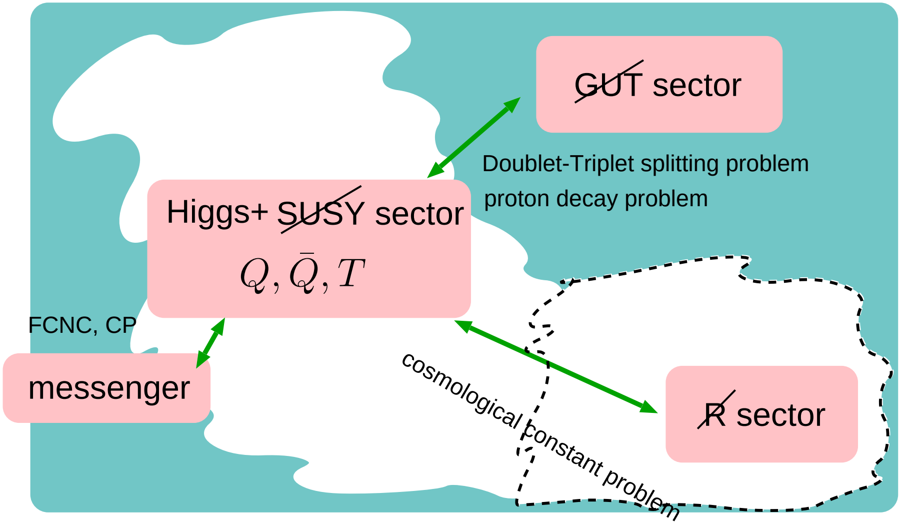
$$K \ni \frac{S^\dagger S}{\Lambda^2} H^\dagger H \qquad F_S = \mu\Lambda$$

$$\Downarrow$$

$$m_H^2 \sim \mu^2$$ (Independent of $\Lambda$ ) !

Size of μ is the same as SUSY breaking terms because μ is the source of the SUSY breaking!!!

## Cosmological Constant driven SUSY breaking



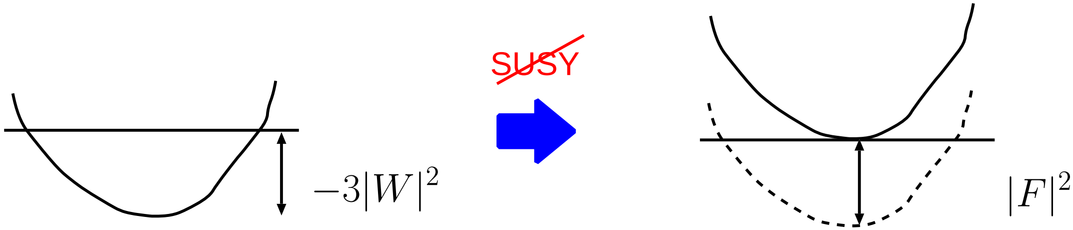

We haven't suceeded to explain the smallness of the $\mu$-term.

We can relate this problem to the cosmological constant problem.

# Cosmological Constant driven SUSY breaking

In any SUSY models

$$\boxed{\Lambda_{CC}^4 = \overbrace{|F|^2}^{\cancel{\text{SUSY}}} - 3\overbrace{|W|^2}^{\text{Supersymmetric}}/M_{\rm Pl}^2 \sim 0}$$

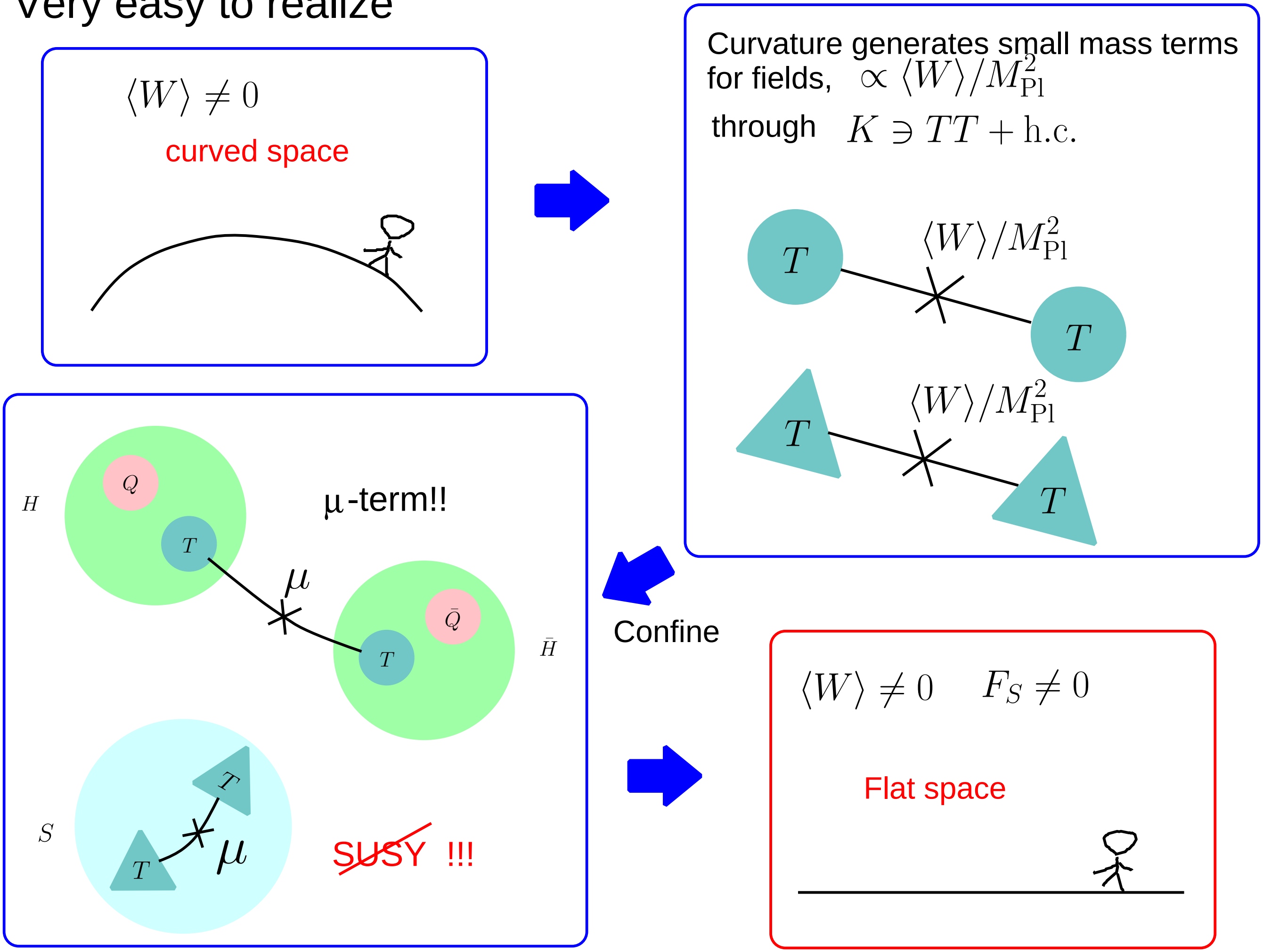



There is always a supersymmetric parameter which has the same size as F!!!

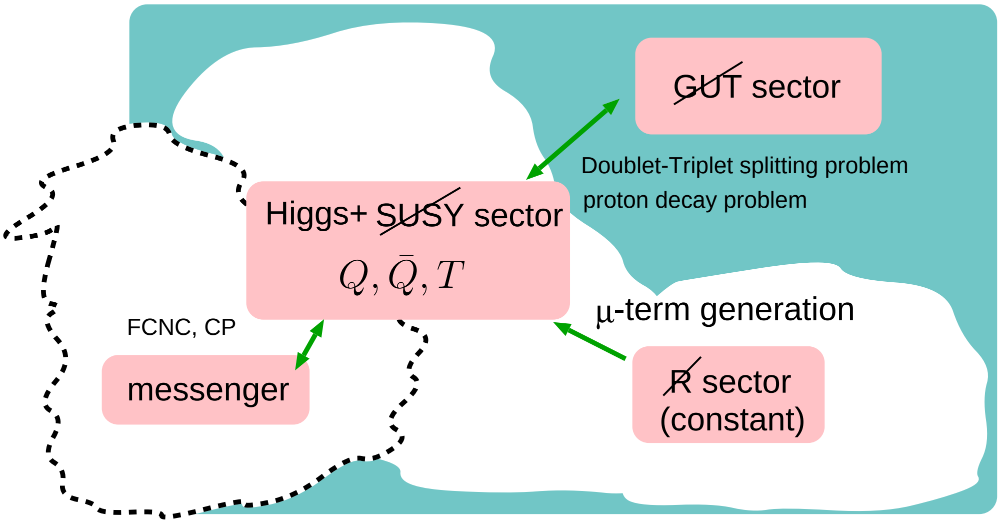
→ Isn't it natural that <W> triggers ~~SUSY~~?

negative cosmological constant

# Very easy to realize



## Gravitational Gauge Mediation




In μ-driven scenario

$$m_{3/2} \sim \frac{F_S}{M_{\rm Pl}} \sim \mu \left( \frac{\Lambda}{M_{\rm Pl}} \right) \ll O(100)\ \mathrm{GeV}$$

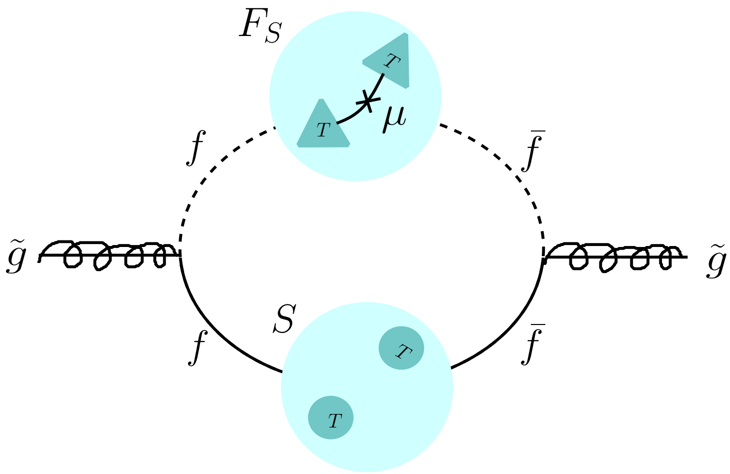
$\longrightarrow$ **Gauge mediation**

gravity mediation requires

$$m_{3/2} \sim 100\ \mathrm{GeV}$$

Gravity is too weak.

Let's just introduce messengers $f, \bar{f}$ (5 and 5* representation)




$$K = T^\dagger T, \qquad W = \mu T^2 + \frac{\kappa}{M_{\rm Pl}} T^2 f \bar{f}$$

confine

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} - \frac{\lambda^2}{(4\pi)^2} S^\dagger S \log \frac{S^\dagger S}{\Lambda^2}$$

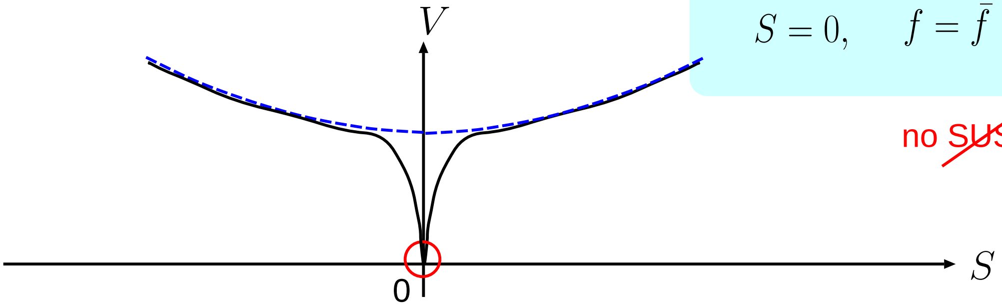
$$W = \mu \Lambda S + \lambda S f \bar{f}$$

But...

$$S = 0, \qquad f = \bar{f} = \sqrt{\frac{\mu\Lambda}{\lambda}}$$

no ~~SUSY~~

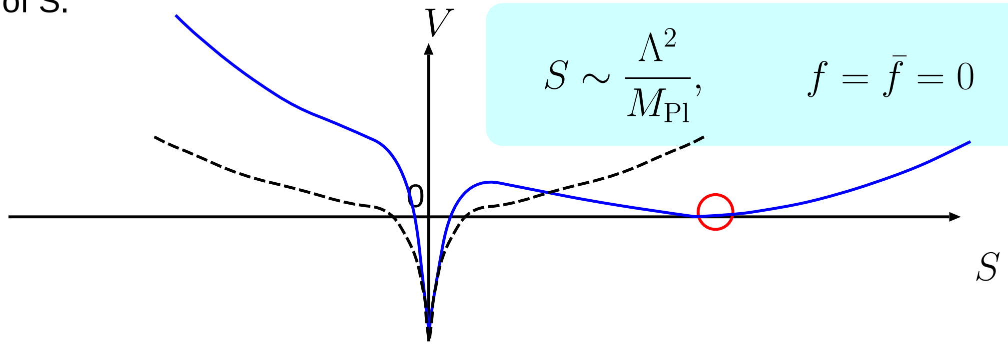
However, situation dramatically changes when we include gravity.




$$S=0, \qquad f=\bar{f}=\sqrt{\frac{\mu\Lambda}{\lambda}}$$

no ~~SUSY~~

Once we include the gravity (1/Mp) effect, we find another vacuum far away from the origin of S.




$$S \sim \frac{\Lambda^2}{M_{\mathrm{Pl}}}, \qquad f=\bar{f}=0$$

~~SUSY~~

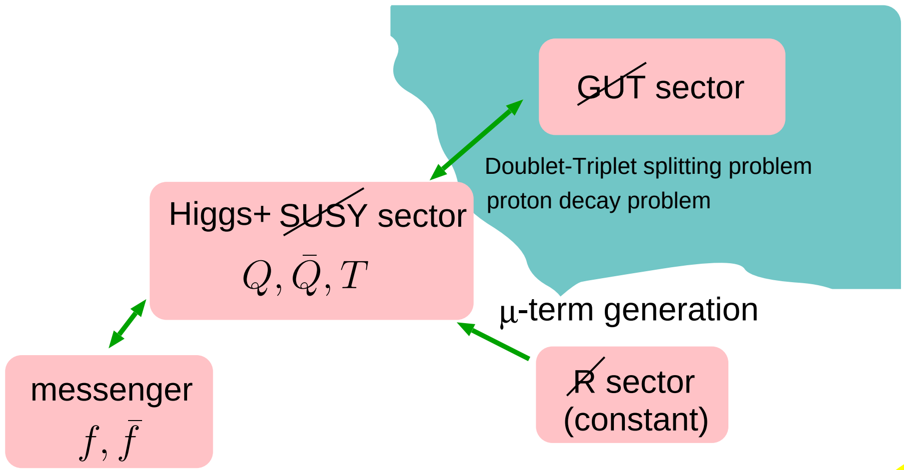
gaugino masses:

$$m_\lambda = \frac{g^2}{(4\pi)^2}\frac{F_S}{S} \sim \frac{g^2}{(4\pi)^2}\frac{\mu M_{\mathrm{Pl}}}{\Lambda}$$

$$\Lambda \sim M_{\mathrm{GUT}} \Longleftrightarrow m_\lambda \sim \mu$$

Indication of the unification of SUSY and GUT breaking dynamics.

# Dynamical GUT breaking

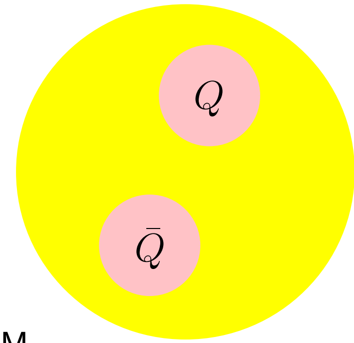



Very Very simple model for GUT is possible again.

$$H \sim (QT), \qquad \bar{H} \sim (\bar{Q}T), \qquad S \sim (TT),$$

and

$$\langle M_{Q\bar{Q}} \rangle \sim \langle Q\bar{Q} \rangle = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 0 & & \\ & & & v^2 & \\ & & & & v^2 \end{pmatrix}$$




SU(5) -> SM

no Doublet-Triplet splitting problem

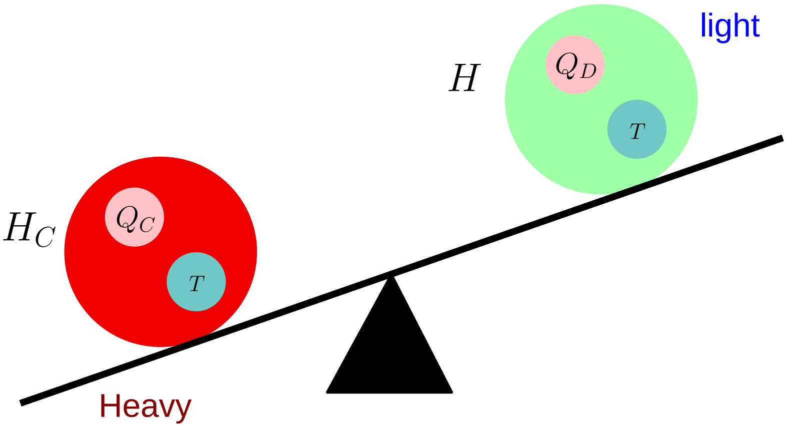
# Doublet-Triplet Splitting Problem

Heavy

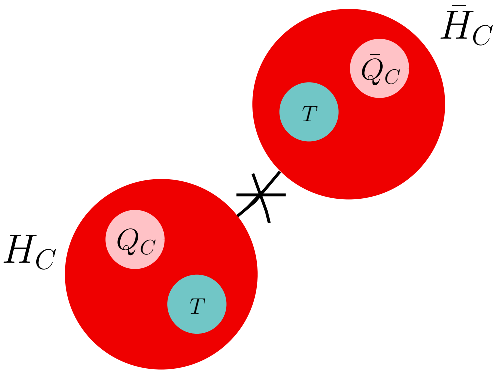
SU(5) $\begin{pmatrix} H_C \\ \hline H \end{pmatrix} \begin{matrix} 3 \\ 2 \end{matrix} \qquad \begin{pmatrix} \bar{H}_C \\ \hline \bar{H} \end{pmatrix} \begin{matrix} \bar{3} \\ \bar{2} \end{matrix}$

light

Why?




mass term like this?




No. This type of mass term induces too rapid proton decay....

## Model

| | SO(9) | $SU(5)_{GUT}$ | (PQ) |
|---|---|---|---|
| $Q$ | 9 | 5 | 0 |
| $\bar{Q}$ | 9 | $\bar{5}$ | 0 |
| $T$ | 9 | 1 | 1 |

$$\boxed{W = mQ\bar{Q} - \frac{1}{M}(Q\bar{Q})^2 + \cdots}$$

We assume there is accidental PQ symmetry in the superpotential.

with

$$\langle M_{Q\bar{Q}} \rangle \sim \langle Q\bar{Q} \rangle = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 0 & & \\ & & & v^2 & \\ & & & & v^2 \end{pmatrix}$$

SU(5) -> SM

strong group: stability of SM vacuum

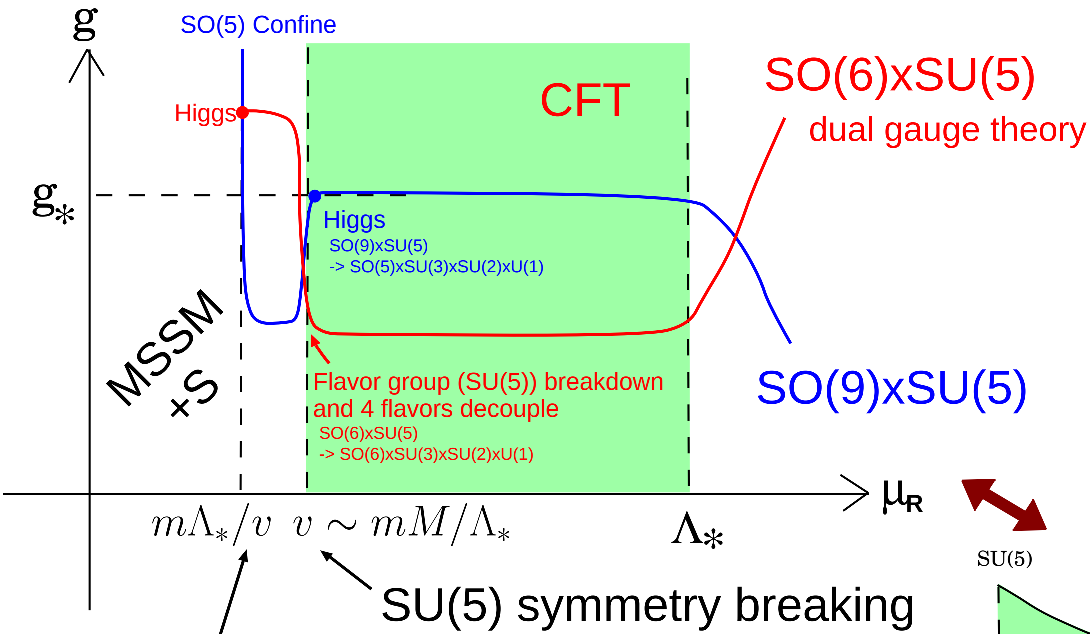
| | | |
|---|---|---|
| SU(N) | N=3 | ⇨ exotic particles |
| Sp(N) | N=2 | ⇨ no SUSY breaking [RK, Kribs] |
| SO(N) | N=6,7,8,9 | |

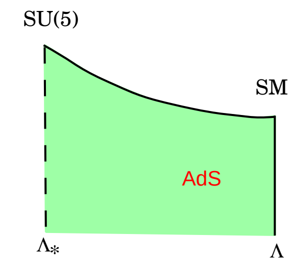
μ-driven SUSY breaking happens

All of them are in the conformal window.

CFT!!!

[Intriligator, Seiberg '95]



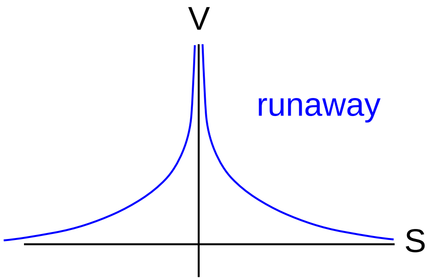

Superpotential plays a role of the Goldberger-Wise field.

Decoupling of the heavy field --> CFT exit (confinement)

There is no coincidence problem between the parameters in the superpotential and the dynamical scale of SO(Nc).

$\Lambda$ is controled by superpotential parameters.

Note: We cannot choose arbitrary breaking pattern.




- $\mathrm{rank}(M_{Q\bar{Q}}) = 0$ SU(5) unbroken

  low energy: SO(9) 1 flavor theory --> No vacuum!!

  symmetry breaking must happen.

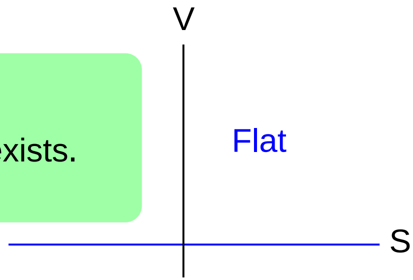
- $\mathrm{rank}(M_{Q\bar{Q}}) = 1$ SU(5) --> SU(4) x U(1)

  low energy: SO(7) 1 flavor theory --> No vacuum!!

- $\mathrm{rank}(M_{Q\bar{Q}}) = 2$ SU(5) --> SU(3) x SU(2) x U(1)

  low energy: SO(5) 1 flavor theory --> Stable vacuum exists. (confining)

  massless d.o.f: $H_u, H_d, S(\sim TT)$




- $\mathrm{rank}(M_{Q\bar{Q}}) = 3$ SU(5) --> SU(3) x SU(2) x U(1)

  low energy: SO(3) 1 flavor theory --> Stable vacuum exists. (Coulomb phase)

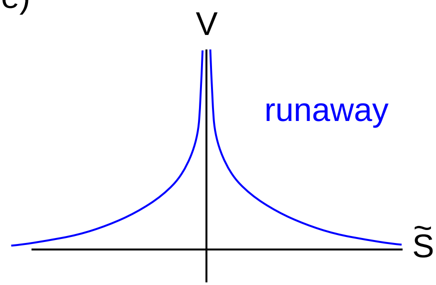
  massless d.o.f: $H_C, \bar{H}_C, S_0, S_+, S_-$

- $\mathrm{rank}(M_{Q\bar{Q}}) = 4$ SU(5) --> SU(4) x U(1)

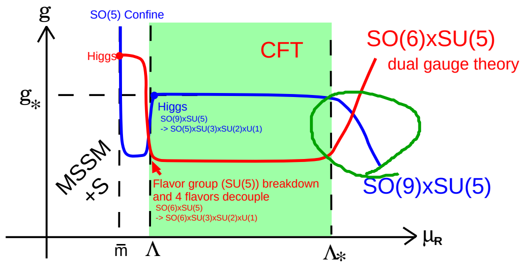
  low energy: confining --> Stable vacuum exists.

- $\mathrm{rank}(M_{Q\bar{Q}}) = 5$ SU(5) unbroken

  low energy: SO(6) 1 flavor --> No vacuum!!



# Doublet-Triplet Splitting




- SO(9) 11 flavors

$$W = mQ\bar{Q} - \frac{1}{M}(Q\bar{Q})^2 + \cdots$$

Seiberg dual

- SO(6) 11 flavors $\quad q, \bar{q}, t$ : dual quarks

CFT but Weakly coupled

$$\begin{aligned} W &= mM_{Q\bar{Q}} - \frac{1}{M}M_{Q\bar{Q}}^2 + \cdots \\ &+ \frac{1}{\hat{\Lambda}}\bar{q}M_{Q\bar{Q}}q + \cdots \\ &+ \frac{1}{\hat{\Lambda}}\bar{q}Ht + \frac{1}{\hat{\Lambda}}q\bar{H}t + \frac{1}{\hat{\Lambda}}Stt \end{aligned}$$

$$\langle M_{Q\bar{Q}} \rangle = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 0 & & \\ & & & v^2 & \\ & & & & v^2 \end{pmatrix}$$

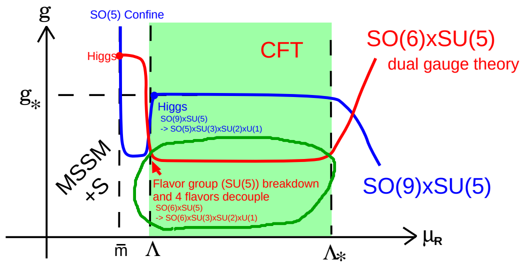
4 flavors decouple $\quad q_D, \bar{q}_D$ $\quad$ <== SU(2) doublet part

- SO(6) 7 flavors

$$\begin{aligned} W &= mM_{Q\bar{Q}} - \frac{1}{M}M_{Q\bar{Q}}^2 + \cdots \\ &+ \frac{1}{\hat{\Lambda}}\bar{q}_C M_{Q\bar{Q}}^{(3\times 3)} q_C + \cdots \\ &+ \frac{1}{\hat{\Lambda}}\bar{q}_C H_C t + \frac{1}{\hat{\Lambda}}q_C \bar{H}_C t + \frac{1}{\hat{\Lambda}}Stt - \frac{1}{v^2\hat{\Lambda}}H_u H_d tt \end{aligned}$$

Still interacting theory
but Strongly coupled

# Doublet-Triplet Splitting




- SO(9) 11 flavors

$$W = mQ\bar{Q} - \frac{1}{M}(Q\bar{Q})^2 + \cdots$$

Seiberg dual

- SO(6) 11 flavors $q, \bar{q}, t$ : dual quarks

CFT but Weakly coupled

$$\begin{aligned} W &= mM_{Q\bar{Q}} - \frac{1}{M}M_{Q\bar{Q}}^2 + \cdots \\ &+ \frac{1}{\hat{\Lambda}}\bar{q}M_{Q\bar{Q}}q + \cdots \\ &+ \frac{1}{\hat{\Lambda}}\bar{q}Ht + \frac{1}{\hat{\Lambda}}q\bar{H}t + \frac{1}{\hat{\Lambda}}Stt \end{aligned}$$

$$\langle M_{Q\bar{Q}} \rangle = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 0 & & \\ & & & v^2 & \\ & & & & v^2 \end{pmatrix}$$

4 flavors decouple $q_D, \bar{q}_D$ <== SU(2) doublet part

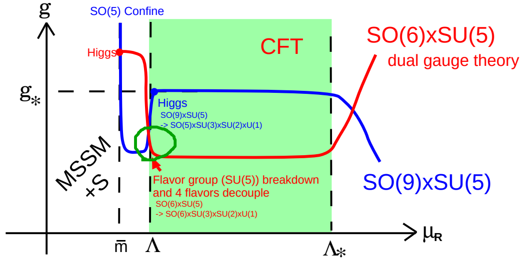
- SO(6) 7 flavors

$$\begin{aligned} W &= mM_{Q\bar{Q}} - \frac{1}{M}M_{Q\bar{Q}}^2 + \cdots \\ &+ \frac{1}{\hat{\Lambda}}\bar{q}_C M_{Q\bar{Q}}^{(3\times 3)} q_C + \cdots \\ &+ \frac{1}{\hat{\Lambda}}\bar{q}_C H_C t + \frac{1}{\hat{\Lambda}}q_C \bar{H}_C t + \frac{1}{\hat{\Lambda}}Stt - \frac{1}{v^2\hat{\Lambda}}H_u H_d tt \end{aligned}$$

Still interacting theory
but Strongly coupled

# Doublet-Triplet Splitting

- SO(9) 11 flavors




$$W = mQ\bar{Q} - \frac{1}{M}(Q\bar{Q})^2 + \cdots$$

Seiberg dual

- SO(6) 11 flavors

$q, \bar{q}, t$ : dual quarks

CFT but Weakly coupled

$$\begin{aligned} W &= mM_{Q\bar{Q}} - \frac{1}{M}M_{Q\bar{Q}}^2 + \cdots \\ &\quad + \frac{1}{\hat{\Lambda}}\bar{q}M_{Q\bar{Q}}q + \cdots \\ &\quad + \frac{1}{\hat{\Lambda}}\bar{q}Ht + \frac{1}{\hat{\Lambda}}q\bar{H}t + \frac{1}{\hat{\Lambda}}Stt \end{aligned} \longleftarrow \langle M_{Q\bar{Q}} \rangle = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & 0 & & \\ & & & v^2 & \\ & & & & v^2 \end{pmatrix}$$

4 flavors decouple $q_D, \bar{q}_D$

<== SU(2) doublet part

- SO(6) 7 flavors

$$\begin{aligned} W &= mM_{Q\bar{Q}} - \frac{1}{M}M_{Q\bar{Q}}^2 + \cdots \\ &\quad + \frac{1}{\hat{\Lambda}}\bar{q}_C M_{Q\bar{Q}}^{(3\times 3)} q_C + \cdots \\ &\quad + \frac{1}{\hat{\Lambda}}\bar{q}_C H_C t + \frac{1}{\hat{\Lambda}}q_C\bar{H}_C t + \frac{1}{\hat{\Lambda}}Stt - \frac{1}{v^2\hat{\Lambda}}H_u H_d tt \end{aligned}$$

Still interacting theory
but Strongly coupled

Seiberg dual again

- SO(5) 7 flavors

It comes back to the original theory, but there is no doublet quarks anymore.

$$W = mM_{Q\bar{Q}} - \frac{1}{M}M_{Q\bar{Q}}^2 + \cdots$$
$$+\frac{1}{\hat{\Lambda}}M_{Q\bar{Q}}^{(3\times 3)}M_{q\bar{q}}^{(3\times 3)} + \cdots$$
$$\boxed{+\frac{1}{\hat{\Lambda}}H_C\bar{H}'_C + \frac{1}{\hat{\Lambda}}\bar{H}_C H'_C}$$
$$\boxed{-\frac{1}{v^2\hat{\Lambda}}H_u H_d S' + \frac{1}{\hat{\Lambda}}SS'}$$
$$-\frac{1}{\hat{\Lambda}}\bar{Q}_C M_{q\bar{q}}^{(3\times 3)} Q_C + \cdots$$
$$-\frac{1}{\hat{\Lambda}}\bar{Q}_C H'_C T - \frac{1}{\hat{\Lambda}}Q_C \bar{H}'_C T - \frac{1}{\hat{\Lambda}}S'TT$$

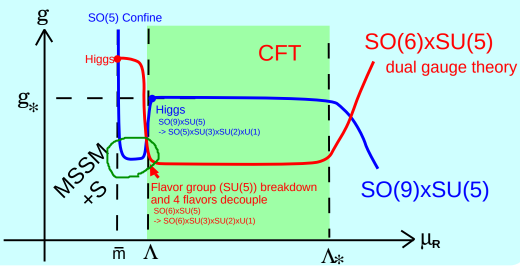
$$\begin{cases} F_{M_{Q\bar{Q}}^{(3\times 3)}} = 0 \\ \Rightarrow \quad M_{q\bar{q}}^{(3\times 3)} = \mathrm{diag.}(-m\hat{\Lambda}, -m\hat{\Lambda}, -m\hat{\Lambda}) \end{cases}$$

mass terms for colored Higgs!!!

$$F_S = 0 \quad \Rightarrow \quad S' = 0$$

massless doublets!!!

6 flavors decouple $Q_C, \bar{Q}_C$




- SO(5) 1 flavor (massless T)

$$W = 0$$

confining

massless d.o.f: $H_u, H_d, S$
with no superpotential

Seiberg dual again

- SO(5) 7 flavors

It comes back to the original theory, but there is no doublet quarks anymore.

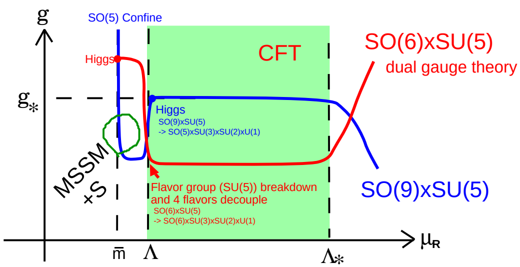
$$
\begin{aligned}
W = & \, m M_{Q\bar{Q}} - \frac{1}{M} M_{Q\bar{Q}}^2 + \cdots \\
& + \frac{1}{\hat{\Lambda}} M_{Q\bar{Q}}^{(3\times 3)} M_{q\bar{q}}^{(3\times 3)} + \cdots \\
& \boxed{+ \frac{1}{\hat{\Lambda}} H_C \bar{H}'_C + \frac{1}{\hat{\Lambda}} \bar{H}_C H'_C} \\
& \boxed{- \frac{1}{v^2 \hat{\Lambda}} H_u H_d S' + \frac{1}{\hat{\Lambda}} S S'} \\
& - \frac{1}{\hat{\Lambda}} \bar{Q}_C M_{q\bar{q}}^{(3\times 3)} Q_C + \cdots \\
& - \frac{1}{\hat{\Lambda}} \bar{Q}_C H'_C T - \frac{1}{\hat{\Lambda}} Q_C \bar{H}'_C T - \frac{1}{\hat{\Lambda}} S' T T
\end{aligned}
$$

$$
\begin{cases}
F_{M_{Q\bar{Q}}^{(3\times 3)}} = 0 \\
\Rightarrow \quad M_{q\bar{q}}^{(3\times 3)} = \mathrm{diag.}(-m\hat{\Lambda}, -m\hat{\Lambda}, -m\hat{\Lambda})
\end{cases}
$$

mass terms for colored Higgs!!!

$$F_S = 0 \quad \Rightarrow \quad S' = 0$$

massless doublets!!!




6 flavors decouple $\quad Q_C, \bar{Q}_C$

- SO(5) 1 flavor (massless T)

$$W = 0$$

confining

massless d.o.f: $H_u, H_d, S$

with no superpotential

## Yukawa interactions

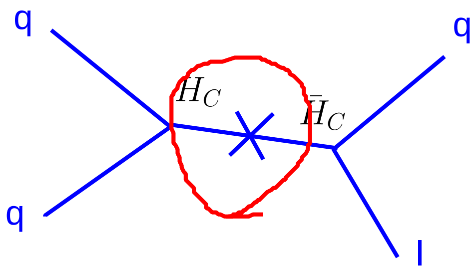
$$W = \frac{f_u}{M_Y}(10)(10)(QT) + \frac{f_d}{M_Y}(10)(\bar{5})(\bar{Q}T)$$

These operators look like irrelevant operators, but actually these are almost merginal operators by the large anomalous dimension in the CFT.

$$D(H) = D(\bar{H}) = \frac{3}{2}R(H) = \frac{12}{11} \simeq 1$$

Therefore, there is no problem with the O(1) top Yukawa couplings. It never hits the Landau pole at high energy.

$\boxed{\text{Colored Higgs mediated proton decay???}}$




No mass term like this!!

colored Higgs is massive by the superpotential term:

$$W = \frac{1}{\hat{\Lambda}} H_C \bar{H}'_C + \frac{1}{\hat{\Lambda}} \bar{H}_C H'_C$$

$\Rightarrow$ $\boxed{\text{No dangerous dim-5 proton decay.}}$

Explicit calculation of the effective superpotential gives

$$W = W_{\text{YUKAWA}} + \frac{y_u y_d}{m} \frac{S}{M_{\text{GUT}}} (QQQL + UUDE + QQUD + UEQL)$$

baryon number violating terms

where S is flat direction.

S is going to be stabilized by the supergravity effect with

$$\boxed{S \sim \frac{M_{\text{GUT}}^2}{M_{\text{Pl}}}}$$

suppression of the dim-5 proton decay

Turn on Gravity

$$K \ni \kappa T^2 + \text{h.c.}$$

$$W = m_{3/2} M_{\text{Pl}}^2 \left( 1 + \frac{T^2}{M_{\text{Pl}}^2} + \cdots \right)$$

These terms modify the vacuum structure a little bit.

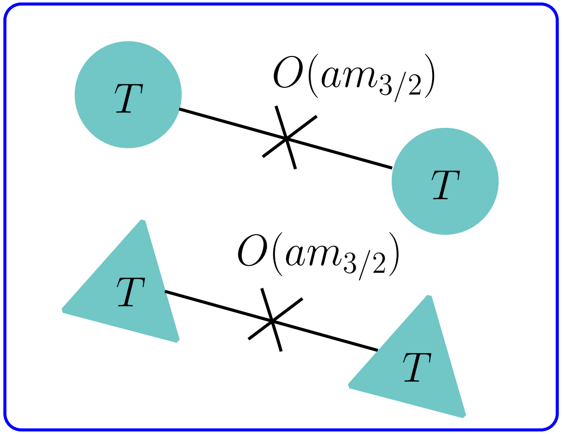
CFT

Enhancement of the coupling by a large anomalous dimension.

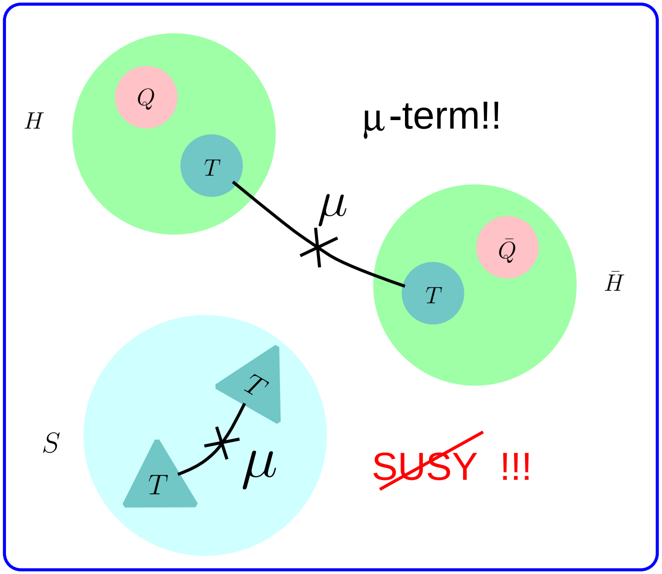
$$K \ni a\kappa T^2 + \text{h.c.}$$

$$W = m_{3/2} M_{\text{Pl}}^2 \left( 1 + \frac{aT^2}{M_{\text{Pl}}^2} + \cdots \right)$$

$$a \sim \frac{M_{\text{Pl}}}{M_{\text{GUT}}} \sim 100$$

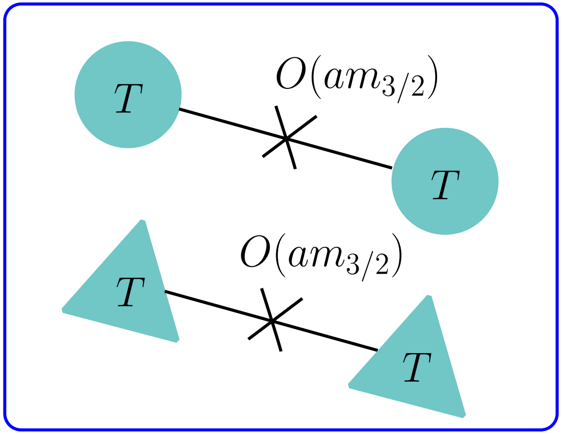



Confine

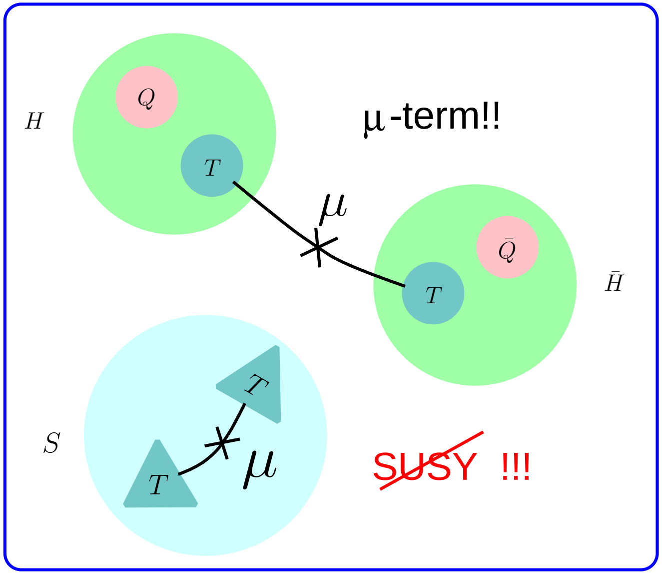


## Consistency

$$a \sim \frac{M_{\rm Pl}}{M_{\rm GUT}} \sim 100$$




Confine



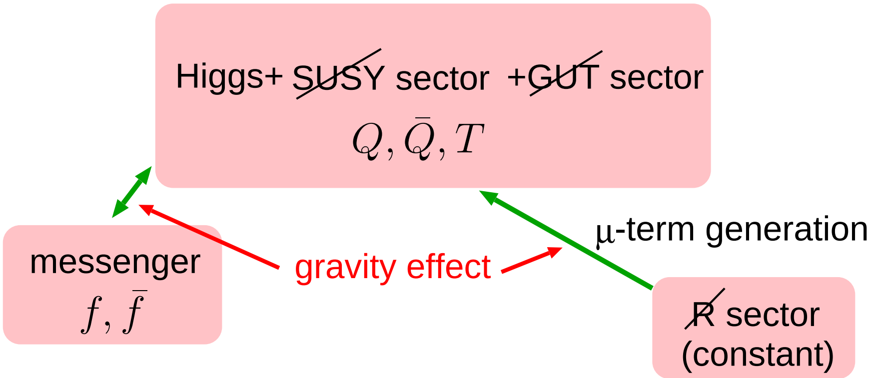

$$\boxed{\mu \sim 100 m_{3/2}} \qquad F_S \sim \mu M_{\rm GUT} \longrightarrow \boxed{m_{3/2} \sim 1\ \mathrm{GeV}}$$

consistent!

$$\boxed{m_\lambda \sim \mu \frac{g^2}{(4\pi)^2} \frac{M_{\rm Pl}}{M_{\rm GUT}} \sim \mu}$$

(gravitational gauge mediation)

Dirty sectors became pretty simple. All the symmetry breaking sectors are unified into three particles Q, Qbar, T



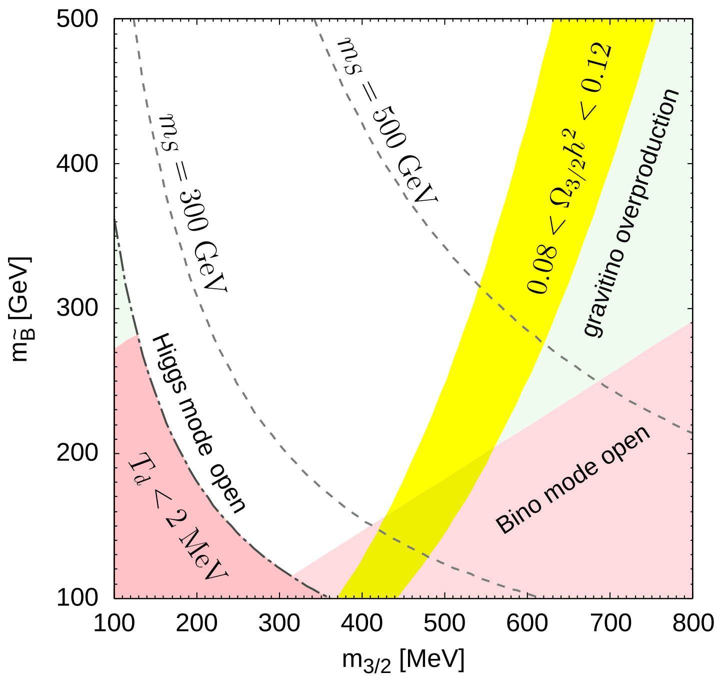

# Moreover...

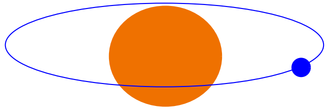
## Gravitino Dark Matter

hep-ph/0611111 [M.Ibe RK]

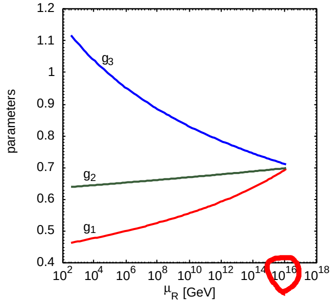
Non-thermal gravitino production from S decays explains the dark matter component of the universe!!

No moduli or gravitino problem in this model.

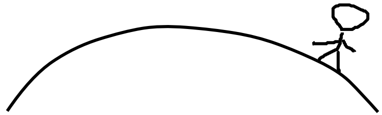




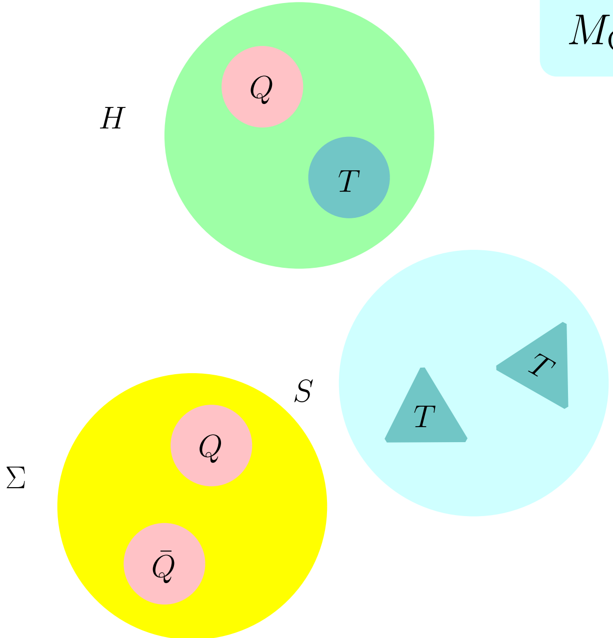
$M_{\text{Pl}} \sim 10^{18}$ GeV




$M_{\text{GUT}} \sim 10^{16}$ GeV



$m_{3/2} \sim 1$ GeV




Dark Matter

$\Omega_{\text{CDM}} \sim 0.1$

μ-term

$\mu \sim 100$ GeV

Higgs soft mass

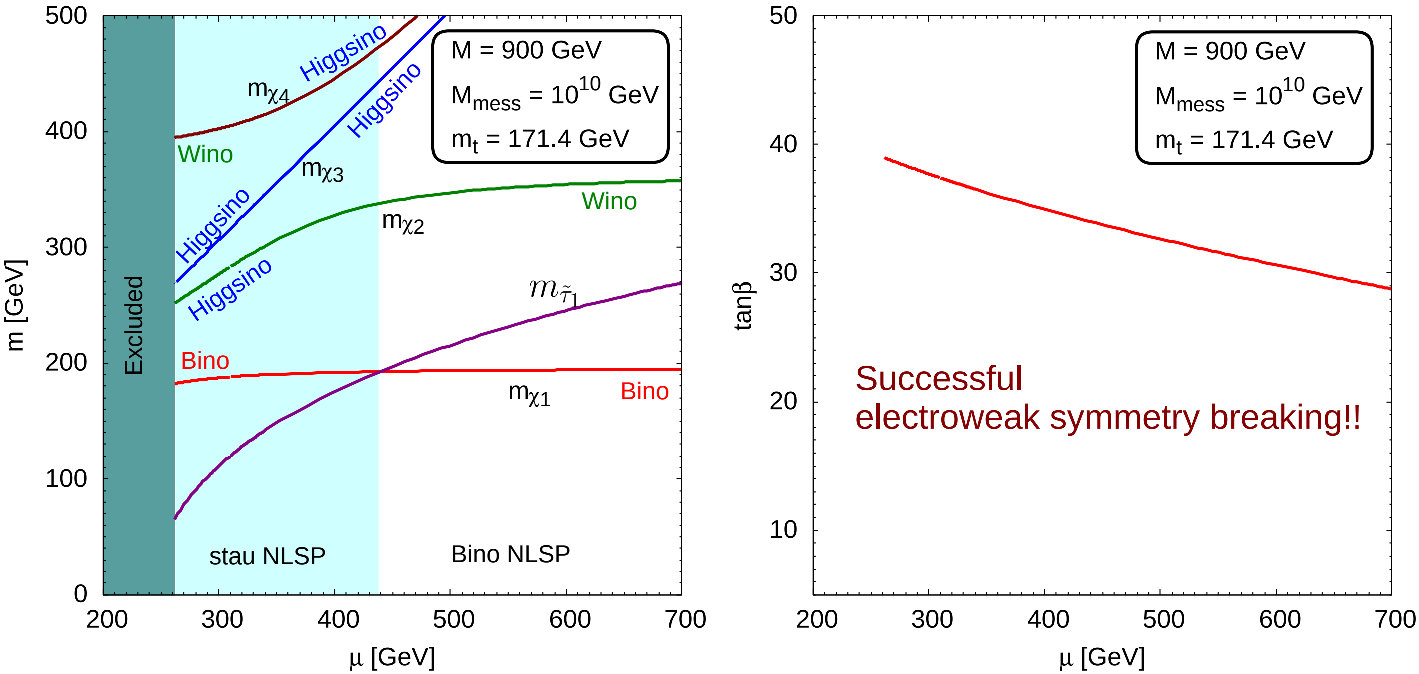
$m_H^2 \sim (100 \text{ GeV})^2$

gaugino/scalar masses

$m_{\text{SUSY}} \sim 100$ GeV

No CP, FCNC, moduli/gravitino, mu,
doublet-triplet splitting or proton decay problem.

# SUSY Spectrum




* There are only three parameters M, Mmess and mu.

* stau NLSP is possible when mu is small. This correlation is an interesting prediction.

* tan(beta) is relatively large.

## Summary

* SUSY has been the leading candidate of the physics beyond the SM. But we did not have an explicit consistent scenario or model. We showed that gauge mediation + supergravity effects solves all the problems without extension of the MSSM below the GUT scale.

* The minimal model of composite Higgs bosons (H~QT) gives a unified picture of Higgs sectors. (Electroweak symmetry breaking, SUSY breaking, GUT breaking are naturally unified.)

* Low energy prediction is a unique SUSY spectrum. It is gauge mediation type with modification in the Higgs sector. In particular, stau NLSP with light Higgsino is a characteristic signature.

* O(1GeV) gravitino dark matter...

## Doublet-Triplet Splitting

Are you lost?

Although the description may not be valid, there are easier ways of understanding the doublet-triplet splitting.

* SO(9) Higgs phase picture:

$$\partial W/\partial Q = 0$$

==>

$$\langle Q\rangle = \overbrace{\left(\begin{array}{ccc|ccccc} & & & 0 & & & & \\ & & & & 0 & & & \\ 0 & \cdots & 0 & & & 0 & & \\ & & & & & & v & \\ & & & & & & & v \end{array}\right)}^{9}\Bigg\}\,5 \quad \Longrightarrow \quad T = \left(\begin{array}{c} \tilde{T} \\ \\ \hline H \\ \bar{H} \end{array}\right)$$

$\tilde{T}$: SO(5) fundamental

$H$, $\bar{H}$: Higgs doublets

=> SO(9)xSU(5) --> SO(5)xSU(3)xSU(2)xU(1)

diagonal subgroup

NO colored Higgs!

* SO(6) dual gauge group Higgs phase picture:

$$\langle q\rangle = \overbrace{\left(\begin{array}{ccc|ccccc} & & & v & & & & \\ & & & & v & & & \\ 0 & \cdots & 0 & & & v & & \\ & & & & & & 0 & \\ & & & & & & & 0 \end{array}\right)}^{6}\Bigg\}\,5 \quad \Longrightarrow \quad t = \begin{pmatrix} H'_C \\ \bar{H}'_C \end{pmatrix}$$

Partner of the Colored Higgs!

Missing partner mechanism!

[Hotta, Izawa, Yanagida '96]

=> SO(6)xSU(5) --> SU(3)xSU(2)xU(1) diagonal subgroup